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CANADIAN COMMITTEE ON OCEANOGRAPHY

The Climate of the Hudson Bay Region

By ANDREW THOMSON, F.R.S.C.

IT is very appropriate that members of the Royal Society of Canada should consider at this Winnipeg meeting of the Society, the role which Hudson Bay plays in the general economy of Canada. From the time, in late September, 1610, that Hudson entered the bay named after him, until around 1880, Hudson Bay was the great channel through which trade and commerce found its way into central Canada.

Largely because of its forbidding climate there has been relatively little development on its shores; indeed, there have been so few settlements that weather records were almost non-existent until twenty-five years ago over the vast area bordering on Hudson Bay. One fact should be kept in mind, however: the temperatures are lower in the Hudson Bay region than in any other area at the same latitude around the world. It was through this region of ice and cold that Button and James and Foxe, the explorers of the seventeenth century, hoped to find the northwest channel to the warm regions of the Pacific. It would have made an incalculable difference to Canadian economics if some branch of the Gulf Stream had been diverted into Hudson Bay to circulate around its periphery, instead of its being an area of subnormally low temperature.

The first continuous day by day records taken in Canada of weather from thermometer and barometer readings at fixed hours which have been published and are available to us, were taken at Prince of Wales Fort, Churchill, Manitoba, during the years 1768 and 1769 and appeared in the first Philosphical Transactions of the Royal Society of London two years later. Unfortunately, this extraordinarily good effort was not maintained and there are only a few interrupted records for Churchill from that time until twenty years ago.

According to international agreement, thirty years of continuous records are considered necessary to give a trustworthy mean value for temperature, rainfall, or other weather element at any station. By this standard, Canada has not a single weather station on the shores of Hudson Bay at which trustworthy mean values have been secured; the following stations (Fig. 1) have records for approximately the number of years indicated: Chesterfield Inlet (although records somewhat patchy) about 30 years; Churchill, 18 years; Moosonee, 22 years; Fort George, 23 years; Great Whale River, 22 years; and Port Harrison, 23 years.

These stations are all located within a mile or so of high-water mark.

There are no other reporting stations in the hinterland until one gets well back to the second line of stations which include the following, with the years of their establishment: Baker Lake (1946); The Pas (1910); Wabowden (1943); Gillam (1943); Trout Lake (1939); Kapuskasing (1920); Nitchequon (1942); and Nottingham (1928).

Hudson Bay

Hudson Bay is the Mediterranean Sea of North America, into which drains a basin of 1,500,000 square miles. It lies between 51°N. and 64°N. latitude and between 78° and 94.5°W. longitude. The extreme length of Hudson Bay from Southampton Island to the southern limit of James Bay is 920 miles and its greatest breadth at 60°N. latitude is approximately 600 miles; its water area is 322,000 square miles. In the middle it averages about 420 feet deep. James Bay is much shallower, averaging about 115 feet deep.

Precipitation

The annual rainfall at the southern end of Hudson Bay is approximately 15 inches with snowfall of 100 inches, or a total precipitation of approximately 25 inches a year. The precipitation decreases northward to a total of between 9 and 10 inches a year, half of which falls as rain and the other half as snow.

On account of the general prevalence of westerly winds, precipitation on the western side of the Bay is about 10 per cent less than on the eastern, consisting largely of a heavier snowfall on the eastern side from October to January.

In the James Bay region the rainy months are June, July and August, but as one goes northward the rainfall occurs a little later. Very little precipitation falls in the Hudson Bay region from December to May, inclusive.

Snowfall is extremely difficult to measure on account of drifting with the wind. It is unusual to have enough snow for travel on the land until late December. The grass protrudes through the snow on the level land through most of the winter. The snow surface becomes extremely hard so that it may be cut into blocks. Despite the hardness of the snow, a strong wind cuts off fine particles and drives them along the surface. With a strong wind the scud may form a layer 100 feet thick and obscure the sun. For aircraft operations this drifting snow creates a serious hazard.

Permafrost

The northern half of Hudson Bay lies in a vast permafrost area in which the subsoil remains permanently frozen throughout the year. As a result, the surface drainage from this land is hindered and lakes and ponds abound. The direct and indirect effects of this permafrost on the local

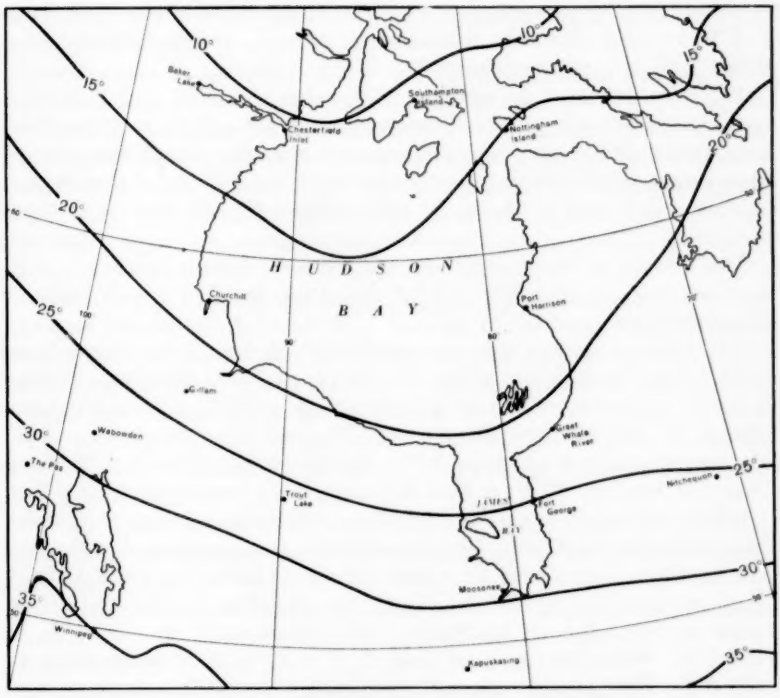

FIGURE 1.—Mean annual temperature of Hudson Bay region in °F.

climate are very considerable; it contributes, for instance, to the abnormally low summer temperature of the Hudson Bay region for this latitude.

Temperature

As already intimated, the Hudson Bay region has distinctly lower average annual temperatures than prevail elsewhere at the same latitude in the Northern or Southern Hemisphere. Siberia is colder than the Hudson Bay region in winter, but much warmer in summer, owing to the chilling effect in the latter of the large body of ice-cold water. The isotherms for central Canada have a V shape with the lower part of the V lying approximately on the north-south axis of Hudson Bay.

Many climatologists define an Arctic climate as one where the warmest month is colder than 50°F. Using this criterion, the boundary line for Arctic Canada runs from Coppermine somewhat south of Chesterfield Inlet to Port Harrison and then bends sharply northward to Fort Chimo. This leaves two-thirds of the Hudson Bay region in the cold summer type (Dfc) of Koppen.

The mean annual temperature (Fig. 1) is 29.5°F. at Moosonee and

decreases gradually northward to 10.8°F. at Chesterfield Inlet and 11.4°F. at Coral Harbour (Southampton Island). At Churchill and Port Harrison, it is approximately 19°F.

The average winter temperature (December, January, and February) is —1° at Moosonee and decreases northward to —22.3° at Chesterfield Inlet and —19.8°F. at Coral Harbour. On the other hand, the summer temperature, (July, August, and September) is 56.2° at Moosonee and decreases northward to 44.0°F. at Chesterfield Inlet and 42.7°F. at Coral Harbour.

The average of daily maximum temperatures during January is 6°F. at Moosonee, at Churchill —11°F., at Port Harrison —8°F. and at Chesterfield Inlet —19.°F.

The absolute extreme low temperatures which have been observed are —60°F. at Chesterfield Inlet and —61°F. at Coral Harbour; stations along the eastern shore seldom get colder than —50°F., the records being Moosonee —52°F., Fort George —52°F., and Port Harrison —51°F. The extreme hottest has been 86°F. at Chesterfield Inlet and 96°F. at Churchill, but only 80°F. at Port Harrison on the eastern side of the Bay.

During the winter season there is little temperature change throughout the twenty-four hours. Few hourly observations are available, but the best data appear to be the Polar Year observations at Chesterfield Inlet, 1932–3. These are too short for definite values, but according to them the coldest hours are from 3 A.M. to 9 A.M. with temperatures of —23.9°F. to —24.1°F., while the warmest hour is 2 P.M. with a temperature of —22.0°F. The average diurnal temperature range in winter is thus approximately 2°F. In summer the daily temperatures range from 46.0°F. at 3 P.M. to 39.3°F. at 3 A.M. and 4 P.M., or a summer diurnal range of 6.7°F.

Climate Change

During the last decades there has been a fairly well marked amelioration of the climate of northern Europe and Siberia, (Ahlmann 1948), and in the Canadian prairies the winters have become milder since 1883 (Marr, 1948). Marr has reported that the tree line in the Richmond Gulf area on the east coast of Hudson Bay has advanced northward in recent years and Hare (1950) believes that it has not yet reached an equilibrium position. Unfortunately, the official records at Chesterfield Inlet and Churchill only go back to about 1925 and these do not show any pronounced warming trend either for the winter season or for the year. Lysgaard (1949) confirms the view that in the present world fluctuations in temperature greater increases have taken place in northern Europe than in eastern Canada.

Ice

The sea-ice begins to form in the Bay about mid-October, is about 18

inches thick by the end of November, and reaches a thickness of 68 inches by the end of April.

Captain Balcom has reported that ice forms in the bays and shores of the west coast of Hudson Bay earlier than in Hudson Strait. Early in October the harbours from Chesterfield northward are usually frozen. The temperatures, as has been noted, are much lower and the local ice is much heavier than in the Strait. Farther south at Churchill and Nelson and on the west coast, the freeze-up begins early in November. An ice front builds up on the shoals fronting the west coast to a width of 5 to 10 miles.

Along the east coast similar conditions prevail, ice reaching out to the numerous islands off the coast to a distance of 70 miles. During heavy winter gales, some of the ice is broken up and piles high on the edge of the fast ice, and this is the source of much of the heavy rafted ice found in the southern part of the Bay in the summer.

The ice begins to disintegrate in the southern part of Hudson Bay in early June and ice from the north keeps moving south, leaving the northern part of the Bay clear.

The ice east of longitude 89°W. moves south faster than the ice of the western half and ice is not away from the west central part of the Bay until after August 15.

According to Captain Balcom the dates when ice cleared and reappeared in any quantity at Chesterfield and Churchill are as follows:

	Chesterfield	*Churchill*
1930	No record—Nov. 4	June 24—Nov. 5
1931	July 6—Nov. 15	June 24—Nov. 11
1932	July 7—Nov. 10	July 8—Nov. 16
1933	July 14—Nov. 11	July 19—Oct. 27
1934	July 16—Nov. 9	July 20—Nov. 1
1935	July 7—Nov. 6	July 26—Oct. 26
1936	July 16—Nov. 1	June 28—Oct. 21
1937	July 11—Nov. 6	July 24—Nov. 1
1938	July 4—Nov. 12	July 5—Nov. 11
1939	July 11—Nov. 30	July 16—Oct. 26
1940	July 8—Nov. 12	July 1—Nov. 8
1941	July 8—Nov. 14	July 1—Nov. 1
1942	July 19—Nov. 18	July 10—Nov. 9
1943	July 14—Nov. 22	July 10—Nov. 5
1944	July 4—Nov. 22	July 7—Oct. 31
Average dates	July 10—Nov. 13	July 9—Nov. 3
Earliest	July 4—Nov. 1	June 24—Oct. 21
Latest	July 19—Nov. 30	July 26—Nov. 16

Climate of East and West Shores

The east and west shores of Hudson Bay show from mid-September to the end of December marked differences in temperature, cloudiness, and general weather conditions. The cause for these differences in weather has been shown by Hare and Montgomery (1949) to be the freezing over of Hudson Bay during these months.

Until 1945, it was generally believed that Hudson Bay was open during the winter except for the belt of fast ice along the shores. However, in that year observers on reconnaissance flights from January to June across the Bay reported an unbroken ice field in the middle of the Bay except for a small lead separating the coastal ice from the central pack and some temporary fissures caused by strains due to storms and tides.

Burbidge (1951) showed from a comparison of the radiosonde data at Port Harrison and Churchill that the air moving across the unfrozen water of the Bay from west to east picks up both heat and moisture. The surface winds in the Hudson Bay region are, from mid-September to December, from the west and northwest and the mean temperature for November at Churchill is 6.8°F. compared with 17.3°F. at Port Harrison, and for December −9.2°F. compared with −1.2°F. As soon as the Bay freezes over, the ice insulates the water below and the temperatures at Churchill and Port Harrison are nearly the same: for January −16.4°F. at Churchill compared with −14.8°F. at Port Harrison, and for February −15.3°F. compared with −16.2°F.

The heating and moistening of the air brings about instability in the lower layers up to heights from 7,000 to 10,000 feet.

Dense cumulus clouds and frequent snow flurries occur on the Quebec shores as long as there is a considerable extent of unfrozen water in Hudson Bay.

Fog

Although fog in itself is of secondary rank as a climate element, it is of importance in the Hudson Bay region because of the extensive use of aircraft. Fog is produced by the chilling of relatively unstable saturated air moving inland from over the Bay and about half of the days with fog reported at stations on the Hudson Bay are during the summer season. Thus, at Churchill, out of an annual total of 31 days with fog, 18 are in summer; at Chesterfield Inlet out of an annual total of 21 days, 12 days are in summer; at Port Harrison 26 fog days in summer out of an average of 46 days annually. From scanty records, it is believed that the fog decreases considerably beyond 25 miles from the shore.

General Aspects of Climate

There are many aspects of climate that cannot be given by statistics. The most important of these is how the ensemble of weather elements affects the human being and his daily activities. Blanchet (1930) discusses this in his report *Keewatin and Northeastern Mackenzie*. The outstanding feature of winter is the wind. In the open places a fresh wind cuts off exposed snow particles and piles them up in huge drifts wherever there is any obstruction, be it as small as a tuft of grass or as large as a house. High winds and low temperatures rarely occur together and there are frequently long periods of clear bright weather with temperatures lower than −30°F.

Spring begins about the middle of April with the commencement of snow melting and continues until the middle of June when the land is clear of snow and the ice is commencing to break up. The early thaw is by evaporation into the air in the bright sunlight at the end of March, and by May 24 snow has melted to such a point that travelling by sleighs is no longer possible.

A good way of marking the arrival of spring apart from the disappearance of snow, is the arrival of the 42°F. isotherm for daily temperature. At this temperature plants will begin to grow and trees show leaves. Similarly the return of 42°F. marks the end of the yearly warm period. Using this criterion, the spring begins at Moosonee about May 15 and the warm period lasts about 120 days. Corresponding data for Eskimo Point to Port Harrison are June 15 and 70 days, and for the northern part of Southampton Island July 15 and 20 days.

Summer lasts from the time the snow disappears in June until the first snowfalls occur in September. During the long hours of sunlight in June and July, flowers, grasses, and shrubs in great profusion are able to reach maturity.

Autumn continues from the time ponds freeze over until the temperatures reach a mean level of —10 to —15° in early December when there is little daylight.

The outstanding seasonal features of the climate on the west coast of Hudson Bay are a long mild spring, with a great deal of cloudy weather, a short summer of rapid growth and fine weather, a long mild fall misty at first then with bright skies and cold, and a cold winter broken with occasional high winds and drifting snow.

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The Pattern of Ice Distribution in Canadian Arctic Seas

By MOIRA DUNBAR*

UNTIL the development of aircraft, knowledge of sea-ice conditions throughout the Arctic was based on the observations of ship-borne expeditions in summer and shore-based wintering parties in winter. Although many excellent records were kept by such parties they have the obvious disadvantage of being isolated both in time and in space. In Canada records with more continuity are available for the areas frequented by whalers in the eighteenth and nineteenth centuries, by the Hudson's Bay Company and other traders, and by regular government patrols. These areas are Baffin Bay, Davis Strait, Hudson Strait and Bay, and Foxe Basin in the east, and the mainland coastal waters in the west. The whalers in particular built up a tremendous store of experience, and a great deal of this lore has been preserved, particularly for the Eastern Arctic, where it played an important part in the development of the Hudson Bay shipping route. For areas beyond the whaling and trading routes, however, information was very sketchy, and observations everywhere were limited to what could be seen from the ground or at best from a crow's-nest.

The use of aircraft has made it possible to observe ice conditions over a large area at one time. The value of this tool was early recognized by the Russians, who have been carrying out ice reconnaissance by air since 1924, and who are far ahead of the rest of the world in the study of the structure, distribution and behaviour of sea-ice. In Canada aircraft were first used for ice reconnaissance on the Hudson Strait Expedition of 1927–8, when conditions in the Strait during a whole year were observed by the RCAF. After this there was little flying north of the mainland until the Second World War, but since then there has been a tremendous increase, mostly, though not entirely, by military aircraft. Flights have been made at all times of year and with a certain amount of regularity. Many have included ice reconnaissance in their programme and this has added considerably to the knowledge of ice distribution, though the picture is still far from complete. In particular one RCAF navigator, W/C K. R. Greenaway, who has probably done more flying in the Arctic islands than any other man, became interested in sea-ice, and since 1946 has made notes of ice conditions on all his flights. The author is indebted to him for much of the material on which this paper is based.

From air observations made over a period of nine years, together with ground records, it has been possible to draw up maps showing winter and

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summer ice conditions throughout the Canadian Arctic. These are by no means final but may serve as a working basis which can be modified as more information becomes available. It should be mentioned in fairness to the many ground explorers who opened up this country that for the most part aerial observations have merely confirmed and supplemented the remarkably accurate picture they built up on such scanty evidence. The only major misapprehension which air reconnaissance has corrected is that the centre of Hudson Bay never freezes. It is not clear how this myth originated or how widely held the opinion was, but it was certainly quoted in several authoritative documents (Montgomery, 1949). This was an area that had not been visited in winter. The conditions in Baffin Bay, the only body of water of comparable size in the Canadian Arctic, were known because from time to time a vessel became frozen in and spent the entire winter in the moving pack. But the centre of Hudson Bay was practically an unknown quantity until flights began to cross it in the Second World War. Finally in 1948–50 the RCAF undertook a series of flights across the Bay at the request of the Meterological Division of the Department of Transport, the Defence Research Board, and McGill University, which proved fairly conclusively that it did freeze (*Arctic Circular* 1948–50).

Figure 1 is a map of winter ice conditions, which unlike summer conditions, seem to vary remarkably little from year to year. This map is divided into areas of (1) continuous ice cover; (2) consolidated pack ice which remains in motion all or part of the winter; (3) unconsolidated pack ice with some open water, which continues in motion all winter; and (4) semi-permanent open patches. The first category includes both pack ice that has been cemented together and shore-fast ice that forms outwards from the coasts and is almost always present to some extent. Where it has been left off the map it is because there is not room to show it rather than because it is absent. The permanent pack ice of the Arctic Ocean is merely indicated as it is outside the area under consideration and only the position of its edge is significant.

A point of interest arising from this map is that the severity of conditions seems to increase from east to west rather than from south to north. All the areas of unconsolidated pack and almost all the open patches are in the east. Hudson Bay, which is perhaps exceptional because of its southerly latitude and inland sea characteristics, freezes rather late, and although it is filled by February or March with fairly solidly cemented pack ice, a number of cracks and leads persist throughout the winter. The Baffin Bay–Davis Strait area, which is more typical, contains more open water than Hudson Bay, particularly in the south and on the Greenland side. Hudson Strait, Lancaster Sound, and Smith Sound all have considerable open water, while in the west the ice cover is almost complete. There is a striking similarity between this pattern and the pressure distribution in winter, with its trough of low pressure in the Baffin Bay area and ridge of high pressure in the northwest. An undoubted correlation does exist.

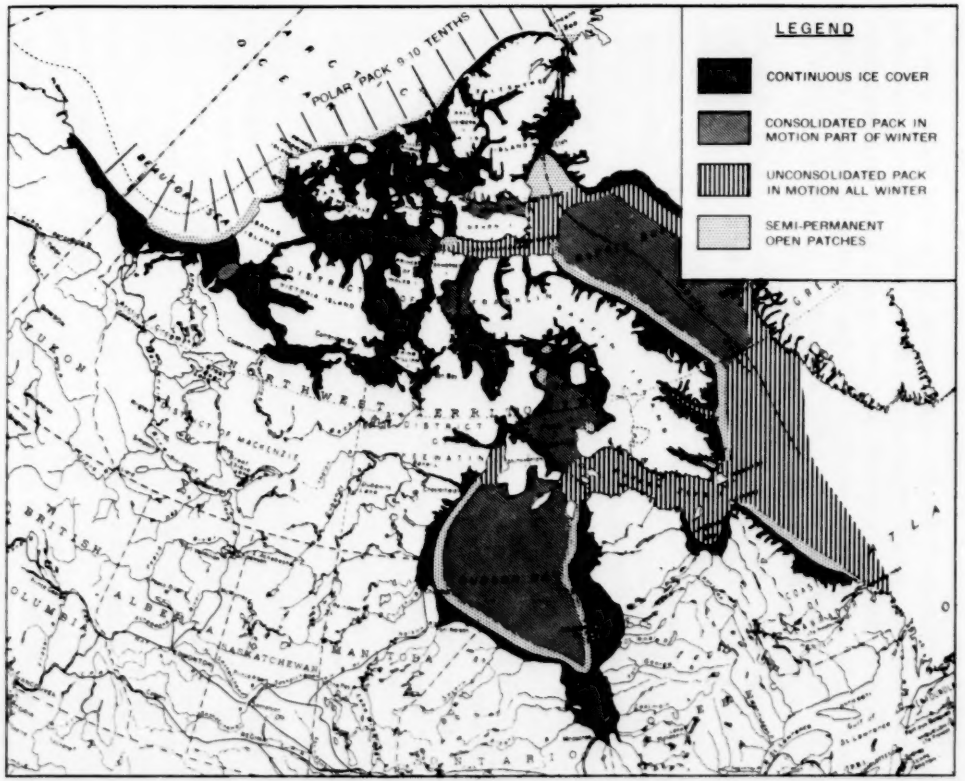

FIGURE 1.—Schematic representation of winter ice conditions.

An even closer relationship would be expected to exist between water temperature and ice and this may be the case, the eastern side being more open to the influence of Atlantic water, while in the west Arctic water is paramount. Unfortunately temperature data are still very scarce, especially in the Western Arctic, and records of winter temperatures are almost completely lacking. It is well known, however, that the west Greenland current carries warm water well into the Baffin Bay area, and this is reflected in the very light ice of the southeast side of the Bay.

Two important factors in accounting for the presence of open water are currents and wind, which keep breaking the ice up as it forms and prevent it from consolidating. It is known, for instance, that strong tidal currents are largely responsible for keeping the ice broken and moving in Hudson Strait and Ungava Bay and in the large bays of southeast Baffin Island. The tides in this area are tremendous, as high as 45 feet at springs in Frobisher Bay. Currents, tidal or other, are also probably the chief factor causing open patches in Foxe Basin and Roes Welcome, in Kennedy Channel, Wellington Channel, Hell Gate, and Bellot Strait. The fact that in the Western Arctic the tidal ranges are on the whole very slight may be significant in accounting for the much lower incidence of open water in this area. Little is known about currents in the Western Arctic. Present information suggests that they are on the whole less strong than those of the Eastern Arctic, although in the narrow channels such as Prince of Wales Strait and Dolphin and Union Strait a considerable tidal current has been observed (Jenness, 1953) and air photographs show strong eddying in Bathurst Inlet.

The influence of the wind is felt both in the breaking up of young ice by storms and in the formation of shore leads, which open and close as the wind direction changes. In Hudson Bay, for instance, leads are seldom present on both sides at the same time. The prevailing westerly wind produces a shore lead on the west coast of the Bay, while in periods of east winds this lead closes and the one on the east side appears. The same occurs in Baffin Bay, and as the prevailing winds in winter for this area are easterly the lead off the Baffin Island coast opens up comparatively rarely. The lead in the northwest at the edge of the Arctic pack also opens and closes with the wind. It is frequently present except between January and March, when the winds tend to blow on shore.

More difficult to account for is the large open patch to the north of Baffin Bay. This is the famous "North Water," well known to the whalers, and is a remarkably stable and unvarying feature. It does not appear to be due to any of the influences so far discussed. It has been suggested that it may be due to continual vertical mixing of the water (A. B. Kiilerich, partly translated and quoted in M. J. Dunbar, 1951) but until winter oceanographic data are available this cannot be confirmed.

An interesting disagreement as to the exact position of the North Water can now be cleared up, in the opinion of the writer, to the satisfaction of

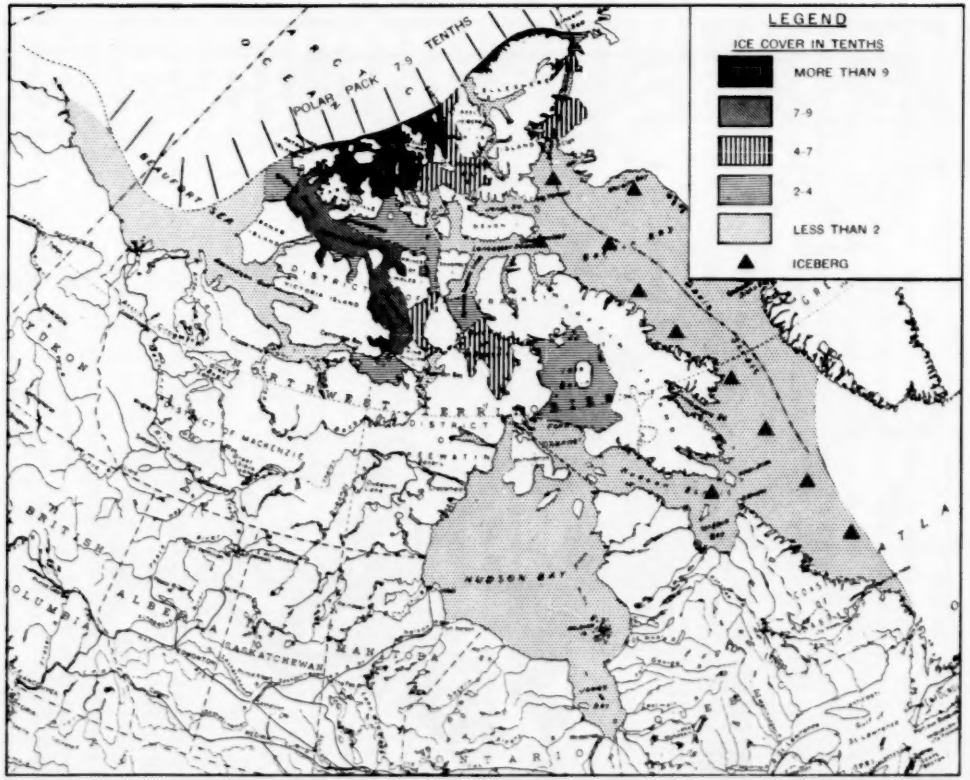

FIGURE 2.—Schematic representation of optimum summer conditions in a light ice year.

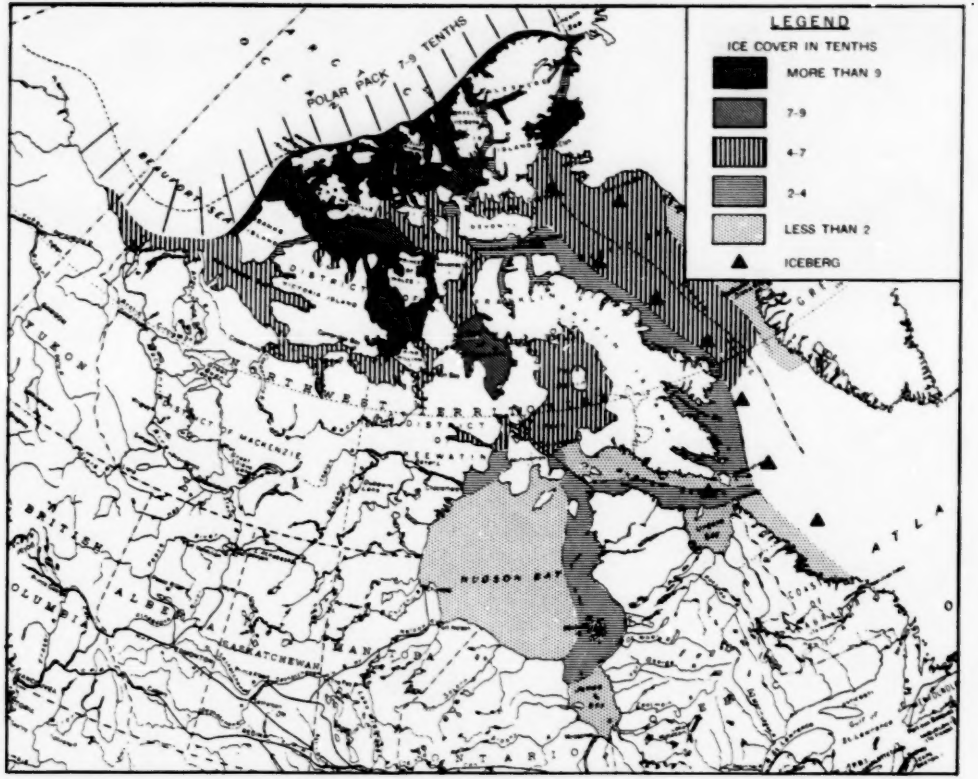

FIGURE 3.—Schematic representation of optimum summer conditions in a heavy ice year showing ice cover in tenths.

both parties. Danish observers in Greenland placed it in very much the area that is shown in Fig. 1 (Kiilerich, quoted in M. J. Dunbar, 1951), whereas in the *Arctic Pilot* the position given is farther south, off the entrance to Lancaster Sound. Air observations confirm that in winter its position is as described by the Danes, whose best opportunity to observe it would be at this season. Its northern edge at this time is very constant, though the southern one is less well defined. In early summer, however, its influence appears to extend southward, and as this was the period at which the whalers made use of it, the position given in the *Pilot* can also be accounted for. Air photographs taken in June, 1953, show open water right down to Lancaster Sound. Further observations of its extent in May and June would be of value. M. J. Dunbar (1951) has shown that in August and September there is a patch of warm surface water (5°C.) to the east of Lancaster Sound, and this should be further investigated at other seasons.

Summer conditions are much more variable than winter, and owing to the prevalence of cloud at this season air coverage is less adequate. No attempt has therefore been made to construct a map showing average summer conditions. Instead two maps have been made, one showing the ice coverage in tenths at the height of an extreme good season (Fig. 2) and the other at the height of an extreme bad season (Fig. 3). The first shows fairly well the areas in which the locally formed ice normally melts completely each summer. These include all those waters shown as having less than two tenths coverage except Peel Sound, and with the possible addition of Barrow Strait and Queen Maud Gulf. These two are subject to invasion by older ice from the west and north respectively, but the local ice normally melts each year. Comparison with Fig. 3 shows that of these areas Hudson Bay and Strait become virtually clear even in the worst years. The small amount present will be largely Foxe Basin ice, which normally comes down into Hudson Strait in July and does not reappear till October but may continue all summer, and which occasionally drifts down into eastern Hudson Bay. Baffin Bay is sometimes full all season of heavy pack which has drifted down from farther north. At such times the North Water may lose its identity, but this is not believed to happen very often. In the channels between the Beaufort Sea and King William Island there have been years when the supply ships have battled ice all summer, and it seems likely that in extreme years the local ice does not all disappear, or that it does so only a few days before freeze-up starts again. Break-up is rather late in this area even in good years, which may be accounted for partly by lack of strong currents and the shallowness of much of the water, and partly by the fact that July is generally a calm period in the Western Arctic.

To turn now to the other end of the scale, the areas which seldom if ever break up are north and west of a line from Prince Patrick Island and Melville Island to the south end of Axel Heiberg Island, and a strip from

M'Clure Strait to Victoria Strait. In the northern area no appreciable open water has been observed, though there must at times be some movement, because we have evidence that ice islands have moved through it from the Arctic Ocean (Moira Dunbar, 1952). The southern area is subject to a certain amount of break-up in many seasons, at any rate from Viscount Melville Sound west, but the heavy old ice does not clear out to any extent. It is likely that the prevailing wind and current tend to pack it southward through M'Clintock Channel and into Victoria Strait, where it becomes grounded and caught among the islands at the south end of the channel, only a small amount of it escaping into Queen Maud Gulf.

Two other areas which are choked with ice in bad years are Kane Basin, which does not always clear out, and the Gulf of Boothia, where the ice from the north packs down and may remain all summer.

Between these extremes are areas where a varying proportion of loose ice remains all season. The movements of this ice are dictated almost entirely by the wind, so a knowledge of the wind speed and direction over a period of a few days will give a good indication of where ice may be expected.

It follows from all this that a good year in one area is not necessarily a good year in another; in fact quite the reverse. A year in which Kane Basin does not clear out will be a very open year in Baffin Bay, whereas an open year in Kane Basin and northwards will fill Baffin Bay with pack ice. From Baffin Bay a certain amount will drift into Lancaster Sound and Hudson Strait. In the same way the more ice comes down from Foxe Basin, the more there will be in Hudson Strait. This ice is likely to be of more than one season's growth, and is a greater hazard to shipping than ice formed the previous winter. This is because as it gets older the salt content is leeched out and the ice becomes tougher and more compact. It also tends to be heavier, owing to growth by hummocking.

When further data become available it may well be found that there is actually less variation between good and bad years than is shown here. There are several reasons for this supposition. The first is that from the incomplete information available it is seldom possible to be sure optimum conditions have been observed, and that adverse conditions experienced on a certain date in a bad year may merely indicate variation in the date of arriving at a more favourable stage rather than complete failure to reach it in that season. There is undoubtedly very considerable variation in the dates of break-up from year to year, and when once it starts the ice disappears very rapidly.

Furthermore, the vessels used by nineteenth-century explorers, many of whose observations have been used, particularly in constructing Fig. 3, were mostly small and low-powered, some with sail only, and certainly none with the power or strength of a modern icebreaker. It is likely therefore that the same ice which they describe as impenetrable might seem less

formidable today. There is also to be borne in mind the undoubted warming of the Arctic which is taking place at present and the cyclic variations of climate that have been shown to have occurred in the past. It might be that conditions in general were worse at the time many observations were made. Too much importance can be attached to this point, however, as is shown by the fact that in 1819 Parry sailed to Melville Island with two small sailing vessels, encountering little real difficulty, whereas in 1947 a powerful icebreaker failed to make the same journey.

The general pattern of increasing intensity of ice from east to west persists through all these maps. The only exception is the line of channels immediately north of the mainland, and these are so narrow and so close to the continental area, with the large expanse of Victoria Island to the north, that they form what is practically an inland waterway and are influenced by the continental climate. It will also be seen that the great inland sea of Hudson Bay, although the most consistently open area in summer, is more completely frozen in winter than some waters far to the north of it. Thus while it exerts a strong modifying influence on the climate in summer, it is in turn influenced by the continental climate in winter.

It would appear, therefore, that factors other than latitude have an important effect on ice distribution. Among the most significant appear to be sea temperature and salinity, currents, and climate. The latter is undoubtedly the most important, with particular emphasis to be given to temperature and winds and the effect of land and sea distribution. In this regard it should be noted that the Arctic Ocean in winter, with its almost complete ice cover, acts as a continental rather than a maritime mass.

There is scope for a great deal of work in the study of sea-ice, which is in its infancy in this country. So much so that there is not even an established terminology, and little has been done on the techniques of collecting data, which is a problem in itself. There is much to be done in determining the relationship of ice conditions to the factors mentioned above and to others such as submarine topography. Most of this work is partly dependent, however, on the collection of complete ice data over a considerable period, and as this is a large and expensive undertaking it is unlikely to occur until some practical need arises. The Russians attained their lead in the study of ice not because they were more curious about it but because to them the northern sea route was economically and strategically important. The Northwest Passage is never likely to be similarily developed, but with the extension of the network of meteorological stations into the Queen Elizabeth Islands a new supply problem has arisen in Canada and with it a need for ice information and for ice forecasting. For the past seven years these far northern stations, which are run jointly by Canada and the United States, have been supplied by the U.S. Navy. As a result of this and their other arctic commitments the U.S. Hydrographic Office has found it necessary to take up ice forecasting and

has made considerable strides in the development of techniques. This year Canadian ships are to take over most of the resupply and it is to be hoped that with the increasing use of Canadian ships in the far north a start may be made here in the systematic collection and interpretation of ice data.

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The Hydrography of Hudson Bay

By H. B. HACHEY, F.R.S.C.

Introduction

The only detailed examination of the hydrography of the Hudson Bay region was made by the author in 1930, and in publishing the results (Hachey, 1931), the earlier knowledge of the hydrography was reviewed. Since 1930, our knowledge of these waters has been supplemented chiefly by the observations made by ships of the Royal Canadian Navy in 1948 (Bailey and Hachey, 1951), and by the annual investigations initiated in 1947 by the Fisheries Research Board of Canada (M. J. Dunbar, 1951). A summary of our knowledge of Eastern Arctic waters generally is given by M. J. Dunbar (1951).

Hudson Bay a Large Estuary

Characteristically, Hudson Bay is an estuary, as indicated by the intense salinity stratification in summer in the upper twenty-five metres of water. Surface salinities in the open bay may be as low as 23 0/00, and salinities at twenty-five metres lower than 31 0/00, with this intensity of stratification decreasing from James Bay to open waters of Hudson Strait.

The horizontal salinity gradient is most intense as it is followed from the mouth of James Bay, with a surface salinity of less than 23 0/00 to the seaward end of Hudson Strait where the surface salinity is 32 0/00 and higher.

The temperature stratification reaches a peak in September and is chiefly contained within the upper twenty-five metres. Recorded surface temperatures in the open bay have been as high as 9.5°C., and temperatures at twenty-five metres ranged from —1.8°C. to 1.5°C. in August, 1930 (Hachey, 1931), and from 0.6°C. to 7.8°C. in September, 1948 (Bailey and Hachey, 1951). The marked salinity stratification of the surface layer of Hudson Bay in summer which gives it the character of an estuary is wholly contained within the upper fifty metres.

Hudson Bay an Inland Sea

In extent, Hudson Bay is an inland sea. Its area is about 200,000 square miles (520,000 sq. km.), with an average depth of about 90 metres, and a maximum depth of about 256 metres. It is completely enclosed on three sides, with a major opening to the northeast, 100 miles (161 km.) in

width, leading into Foxe Channel and Hudson Strait. A minor opening, Roes Welcome Sound, also leads into Foxe Channel. The characteristics of the deeper waters of the Bay are oceanic in that the salinities are those of the open ocean.

The General Circulation

The general circulation of Hudson Bay proper has been dealt with in earlier publications (Hachey, 1931 and 1935; Dunbar, 1951; Canada Dept. Mines and Technical Surveys, 1954). In general, the circulation is anticlockwise, with a southward flow on the west side and a northward flow on the east side of the Bay. The predominant movement in the surface waters is from James Bay northward along the eastern shore, holding close to the coast.

The outward flow from Hudson Bay is evident as a dominant easterly set along the northern side of Digges Island at the western end of Hudson Strait on the south side, which constitutes a constantly outward current. An inward movement of water along the northern side of Hudson Strait is indicated by the drift of icebergs, which are commonly found beyond Big Island to the north and midway through the Strait, and upon occasion found in Hudson Bay itself.

The ice movements from Foxe Channel, which take place on a large scale, are indicative of the movements of more northerly water into Hudson Bay and Strait. Tidal observations in Fisher Strait, south of Southampton Island, have indicated a preponderance of flow southwestward.

In 1930, five hundred drift bottles were released in Hudson Bay (Hachey, 1935). The experiment was remarkable in the number of returns, and in the fact that the returns have continued even to the present year. Ten per cent of the bottles were recovered, and from one lot, 17 per cent. The returns were heaviest in 1931, when twenty-two were received, and gradually decreased until 1936, when only two were reported. In each of the years 1938, 1939, 1942, 1945, 1950, 1952, and 1953, one drift-bottle return was received. All the bottles recovered were taken from within the Bay, and the plotted probable courses of these bottles confirm the anticlockwise circulation of the waters.

The Tides in the Hudson Bay Region

Details of the tides in the Hudson Bay region are published annually by the Canadian Hydrographic Service (Canada Dept. Mines and Technical Surveys, 1954). In Hudson Bay the rise of the tide from datum ranges between 1½ and 2½ feet at Port Harrison on the east coast, to between 11½ and 15 feet at Churchill on the west coast.

In Hudson Strait the mean rise of the tides from datum ranges between 8 and 11½ feet at Digges Island at the inner end of the Strait, to between 31½ and 41 feet at the mouth of the Koksoak River at the head of Ungava Bay. Recent observations in the Koksoak River area have, it is believed,

recorded tides higher than any in the world, exceeding even those of the Bay of Fundy.

Seasonal Cycle in the Surface Layer

The hydrographic data available for Hudson Bay are almost wholly related to the months of August and September, and these data indicate that the seasonal changes in temperature and salinity take place almost wholly within the upper fifty metres, which for our purposes constitute the surface layer.

During the winter months, Hudson Bay is completely ice covered, with the exception of "leads" of open water, which vary in extent and position (Hare and Montgomery, 1949). While no data are available on the salinity of the water under the ice, on the average, for the upper fifty metres, it might be estimated as 30 0/00, with a temperature of approximately —1.6°C. With the advent of spring, the "break-up," movement and melting of the ice cover, and increase in drainage from the land, there is a lowering of the salinity of the immediate surface waters, and this is the beginning of the stratification which develops in the upper layer. The lowering of the salinity continues with the extended period of the break-up of the ice, a period which is prolonged through the blocking of Hudson Strait by the ice from Foxe Channel. Gradually, as the ice disappears, the immediate surface water temperatures increase and temperature becomes a factor in furthering stratification in the upper layer. The process of heating and freshening is eventually carried down to a depth of approximately fifty metres, the maximum stratification probably occurring in early September. In September, the heat losses exceed the heat gained and surface temperatures decrease. Decreasing surface temperatures bring about increased surface densities and initiate a process of vertical mixing, which is accelerated by wind and wave action. Finally the "annual overturn" has been completed, extending probably to depths of fifty metres, and the whole layer is at a temperature which approximates the freezing point of these waters.

The Deeper Waters

Below fifty metres, and extending in places to depths of more than two hundred metres, is a cold saline body of water with temperatures ranging generally between —1.0°C. and —1.8°C. and with salinities ranging between 32.00 and 33.50 0/00, which seemingly undergoes very little change from season to season or from year to year. As shown by Bailey and Hachey (1951), the small changes in temperature and salinity of these deeper waters that have been noted between 1930 and 1948 may be of considerable significance in indicating the varying intensity of the "Atlantic influence" on more northerly waters. The magnitude of this "Atlantic influence" is of considerable interest to the Greenland cod fishery. This fishery presumably exists at the present time because of the stronger

"Atlantic influence" of recent years, which is responsible for water temperatures suitable to the cod.

The question of the replacement of these deeper waters is of fundamental interest. It is axiomatic that where fresh water from continental drainage mixes with saline ocean waters, the light water is dispersed from the area of mixing. As this process in nature is more or less continuous, although varying in intensity, there must always be a renewal of the more saline waters in the mixing area. If the cold, saline body of water below fifty metres in Hudson Bay is involved in such a mixing process, then there must be a renewal on some scale, however small. Otherwise, enclosed as it is in a deep basin, with only a comparatively narrow submarine exit to Hudson Strait, this body of cold saline water is dynamically dead. A comparison of the waters of Hudson Bay in 1930 and 1948 (Bailey and Hachey, 1951) has shown that the characteristics of this cold saline body of water below fifty metres were, in the respective years, as follows:

1930: temperatures of —1.8°C. with salinities between 31.50 and 33.17 0/00.

1948: temperatures less than —1.0°C. with salinities between 32.50 and 33.50 0/00.

These observed variations at least indicate a replacement or renewal of the deeper waters of Hudson Bay on some scale, however large or small.

It is improbable, because of the lower salinities observed in the upper fifty metres in the late summer, that the deeper waters of Hudson Bay are involved in the "annual overturn" within the bay, that process being brought about by the cooling and sinking of surface waters. The lower temperatures of waters below fifty metres can, with our present knowledge, only result from surface chilling, but the comparatively high salinities associated with these lower temperatures suggests that such surface chilling must have taken place outside of the Bay, either in Foxe Channel or Foxe Basin or even in Hudson Strait. Such reasoning implies that replacement of these deeper waters within the Bay takes place only in the colder months, for only at such times is there possibly a source of water of such characteristics in Hudson Strait and Foxe Channel. An examination of published data (Hachey, 1931; Bailey and Hachey, 1951) for the months of August and September will show that salinities of 33 0/00 or greater in Hudson Bay are associated with temperatures of —1.0°C. or lower, while in Hudson Strait such salinities are associated with temperatures between 0.0° and —0.6°C.

Discussion

The origin of the deeper waters of Hudson Bay with temperatures less than —1.0°C. and salinities greater than 33 per cent offers considerable scope for conjecture. It is difficult to conceive of water of such characteristics being produced within the Bay, for it must be assumed that the chilling took place in the upper layers. If such is the case, then at some

time previous to the "freeze-up," the surface layer of lower salinities as observed in the months of August and September must have been almost completely removed from the bay. To deal with this problem thoroughly, we need temperature and salinity data for the water column under the winter ice.

Again we may conjecture that this deep, cold, saline water is fed into the Bay at the greater depths from Foxe Basin, and unfortunately we do not have the data to fix the characteristics of the waters which are carried southward to Foxe Channel. It is not likely that salinities between 32 and 33 0/00 are characteristic of surface waters from the Polar Seas, and even if such waters were available at the greater depths of Foxe Channel and Basin, we would still have the problem of the origin of such waters.

We can, strictly on theoretical grounds, consider that with the advent of the colder months the more saline surface waters of Hudson Strait are chilled to their freezing point of approximately —1.7°C., in part by tidal mixing on a large scale. This process of chilling produces a heavier type of water than that which is formed in the Bay by the same chilling processes. The dynamical tendency is then towards a seaward flow of the lighter Bay waters, and an inward flow of the colder, more saline, and heavier waters from Hudson Strait. As the chilling process progresses throughout the northern latitudes and the continental drainage is reduced to a minimum, there is little augmentation of the surface layer in Hudson Bay. By freeze-up time the waters of Hudson Bay are quite uniform from top to bottom, at a temperature just short of the freezing point and of a salinity of approximately 32 to 33 0/00.

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Production of Life in Hudson Bay

By A. G. HUNTSMAN, F.R.S.C.

A VERY considerable variety of plant and animal life is to be found in Hudson Bay. Since this bay lies between latitudes 52 and 62°, it would be expected to have life resembling in character and amount what is known for sea waters in similar latitudes on the European coast and on our Atlantic and Pacific coasts. This is far from being the case. If it were, Hudson Bay would have species that characterize the northern part of the temperate zone as well as one of the most productive fisheries in the world. This is to judge merely from the waters corresponding in latitude, which are for Europe the North Sea and other waters around the British Isles and southern Norway, for the Pacific the coastal waters of British Columbia and southern Alaska, or for the Atlantic the waters of the Labrador Current.

In addition to various materials, life requires light and heat. That Hudson Bay is in the temperate zone assures it the light characteristic of that zone, but it does not assure the heat. Lake Athabasca and Great Slave Lake to the west of the northern part of Hudson Bay have warmer climates in spite of being at elevations of 690 and 520 feet respectively above sea level and they have considerable fisheries. Lack of heat is a definite handicap for production of life, as is evident in the little life found at the low temperatures of great altitudes under a high sun. There may also be other factors.

Although very little has been done to reveal the character of the life in Hudson Bay, that little does provide a definite and consistent picture. The forms are almost wholly arctic, but with some in the southern part that are subarctic; and there is a definite gradation into merely boreal forms on passing into the fresh water of the rivers. Of the plants, the diatoms of the open Bay are those native to and important in the Arctic Ocean; near the mouth of the Bay they are more abundant and in better condition than farther in, irrespective of temperature or time (Davidson, 1931). All the seaweeds (40 species) are such as have been reported for the Arctic, and are those of a deep estuary in contrast to the kinds found in Hudson Strait (Bell and MacFarlane, 1933). Of the microscopic unicellular animals, the Foraminifera consist mostly of species which are characteristic of arctic conditions and like those of Nova Zembla and in Baffin Bay and Davis Strait (Cushman, 1922). The hydroids are very few both in the open Bay (4 species, all arctic) and at Churchill on the west coast, (6 species, all arctic). Only two were taken in the brackish waters of James Bay at

the south end of Hudson Bay, and one of these was not known to be arctic. In Richmond Gulf on the east coast of Hudson Bay there were 18 species, of which 15 were definitely arctic, and in Hudson Strait, 26 species, 20 being definitely arctic. The hydroids were definitely more numerous in shallow water on the east coast and also in Hudson Strait (Fraser, 1931). Hydroids, therefore, become more numerous and the proportion of sub-arctic forms increases along the course of the circulation of the water south along the west coast and north along the east coast to Hudson Strait on its way to the Atlantic.

The Bryozoa, of which 32 species were found in the Bay and 43 more in the Strait, were nearly all arctic and mostly circumpolar (Osburn, 1932). The 29 species of amphipods that were found were arctic forms, of which three are apparently confined to the Arctic; only one species (*Monoculodes edwardsii*) seemed possibly to be a more southern form (Shoemaker, 1927). The 13 species of ascidians that were found were almost wholly arctic and included one species (*Rhizomolgula globularis*) that reaches a lower latitude in these waters than anywhere else. Only one species, which was taken on the east coast, was indicative of a more southerly fauna (Huntsman, 1922). In general, the marine fishes of Hudson Bay are true arctic species, only one (*Cyclopterus lumpus*) being a typical North Atlantic form (Vladykov, 1933). The latter, however, is a peculiar variety of the species and has been found only on three occasions, at or near Churchill on the west coast of the Bay in 1920, 1929, and 1930.

With varied and varying conditions, and with the various species requiring more or less diverse conditions, the situation can perhaps be best appreciated by considering the distribution of several arctic and temperate species. The beluga or white whale is an arctic form that lives both in Hudson Bay near Churchill and in the St. Lawrence estuary near the mouth of the Saguenay where the surface water is particularly cold. Individuals have even got as far south as the Bay of Fundy where again there is particularly cold water for the latitude. The polar cod, another arctic species, occurs both in the deep open part of Hudson Bay and also in the similarly very cold water of deep inlets along the outer coast of Labrador and the north shore of the Gulf of St. Lawrence. The Greenland cod, first found in Greenland, is distributed in through Hudson Strait to all shores of Hudson Bay, as well as down along the Labrador coast and into the northern part of the Gulf of St. Lawrence.

As typical species of temperate waters, the haddock reaches only as far north as Newfoundland, the lobster reaches the Strait of Belle Isle, the herring reaches some distance north along the outer coast of Labrador, while the common cod, the salmon, and the halibut reach the mouth of Hudson Strait. None of these are to be found in Hudson Bay.

Whatever may be the explanation, there has been consistent failure to develop a commercial fishery out in Hudson Bay (Huntsman, 1931; Hachey, 1931). In contrast, a few strictly marine fish (Greenland cod and

capelin) can be caught along the shore. In rivers and their outflows, quite limited quantities of freshwater and anadromous fishes (pike, pickerel, suckers, cisco, whitefish, trout, and sturgeon) may be taken (Walker, 1931).

As it happens, conditions have in recent years become more suitable for the common cod on the west coast of Greenland, which is farther north than Hudson Bay, and also north of Norway quite far into the Arctic Zone, to latitudes of 70 to 75°. The important fisheries thereby produced are related to movement of Atlantic water northward, the stock of cod north of Norway being "found to be localized in the boundary region of the West Spitsbergen Current, of Atlantic water, and the Bear Island Current, of arctic water" (Graham, 1953). Similarly, the Atlantic water passes northward along the west coast of Greenland and gives fisheries there, which have very considerably increased in extent in recent years. Where the arctic water passes southward there are no such fisheries for cod, as on the east coast of Greenland and on the east coast of Baffin Island. Hudson Bay receives its water from the north, and Atlantic water has but a slight influence in Hudson Strait with arctic water issuing from it and with arctic water also passing from the north across its mouth.

Although the distribution of cod has extended and they have become more abundant to the north in recent years where Atlantic water goes, there seems to be but little evidence that they have extended northward where arctic water moves south, as on the east coast of Greenland and on our coast. This is doubtless owing to the sharpness of the transition from cold to warm water, as determined by movement of the cold water close along the shore in intimate relation with pronounced geographic features such as the jutting Grand Bank of Newfoundland.

The complexities in distribution of arctic and subarctic forms of life that have been described are well shown by M. J. Dunbar (1953, fig. 1), who considers the subarctic zone, usually with important fisheries, to extend from Newfoundland waters only to Hudson Strait on our coast, but to the southern part and most of the west coast of Greenland in higher latitudes, and also to consist of the waters from Iceland to Spitsbergen in Europe in still higher latitudes. This more northern location of the subarctic on going eastward across the Atlantic is in accordance with the circulation of the water (Dunbar, 1953, fig. 3).

In waters that on this basis are arctic in character rather than subarctic, there are no fisheries of any consequence, as in Hudson Bay and the waters north of it, on the east coast of Baffin Island, on the east coast of Greenland north of Iceland, and north of Spitsbergen. At present, fisheries that are prosecuted year after year form our only reliable evidence of comparative productivity of life. The amount of life found at any one time is not a very good criterion because it may represent an accumulation over a long period rather than the amount produced in a standard unit of time such as a year.

We have as yet very few of the details on which to base proper judgment of the reasons for low productivity in arctic waters. Little light and low temperature are obvious factors, but their precise effects on the kinds of life that are suited to such conditions are not yet known. It might be argued that even inside the Arctic Zone there could be high productivity with such light and heat as are there. In Hudson Bay indeed there is certainly more than enough light and to quite an extent enough heat to give a fishery like that north of Norway. At present, we can merely suggest what may be the other factors that come into play.

The hydrographic facts show Hudson Bay to be a deep estuary, and its flora and fauna are in accord with this condition. Estuaries may or may not be very productive, depending upon the way in which the fresh water is mixed with the sea water. In the St. Lawrence estuary, the fresh water is mixed very effectively with the deep sea water near the mouth of the Saguenay, so that the surface water is exceptionally cold. This does not produce large fisheries until the rich mixed water spreads near the surface on passing the Gaspé peninsula and reaching the extensive Magdalen Shallows which form the southern part of the Gulf. The Saint John and other rivers discharge into the Bay of Fundy along the west side of its outer half a very large amount of fresh water that is mixed with much deep sea water by heavy tidal action in the Reversing Falls at Saint John and in the Passamaquoddy archipelago near the mouth of the bay. There results a very high production of life where the mixed water passes along the coast of Maine, and the fish food therefrom is brought back into the Passamaquoddy region to furnish a very great fishery for herring and other fishes. In contrast, the *very* heavy tidal action in the comparatively shallow water of the inner part of the Bay of Fundy and the associated basins and estuaries keeps this water so turbid and hence impervious to light that it has a very low productivity. Accordingly the fisheries there are quite limited.

In Hudson Bay, there is strong tidal action to mix deep with surface water only at the mouth and through Hudson Strait. The Bay itself is broad and has only moderate tidal rise and fall. Consequently, as the hydrography suggests, the deep water that occupies the greater part of the Bay doubtless remains virtually without change throughout the year. The nutrient salts in relation to the bottom are not brought to the surface for plant growth to any great extent either by tidal action or by the seasonal overturn that occurs in many freshwater lakes. The fresh water that enters the Bay from the Saskatchewan and other large rivers all the way from Churchill around the south end of the Bay is mixed only with the surface water (coming from the northwest portion of the Bay) down to a depth of about 25 metres (14 fathoms). In this way the production of life is much restricted. Conditions evidently improve along the course that the water takes, being better in the shallows along the east coast of the Bay and still better in Hudson Strait. But, even in the Strait, where conditions

are at their best, they fall far short of those on the outer coast of Labrador, which in turn are much inferior to those around Newfoundland.

Other factors than deep tidal mixing may bring deep water to the surface and maintain high production of life. Movement of warm water northward into progressively cooler latitudes, as on the European coast, results in continuous overturn by sinking of the surface water when cooled, but Hudson Bay has water that comes from the north. The upwelling that occurs off the west coasts of North and South America and of Africa gives high productivity, but it does not occur in Hudson Bay. The cyclonic storms that sweep northward along the east coast of North America and reach the waters of northern Europe in quite steady succession are more or less effective in overturning waters sufficiently exposed to them, but these are represented but slightly in the Hudson Bay region. Hudson Bay lacks factors that will give high productivity of life in water that is at all deep. But the fisheries of Hudson Bay are by no means negligible, at least for local use. Even more than elsewhere, it is the shore fisheries, particularly for anadromous fishes, that offer the most promise.

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